# Climate controls of decadal drought frequency in the conterminous United States

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**Abstract**. The primary modes of drought frequency in the conterminous United States during 1900-1999 are identified through rotated principal components analysis (RPCA). The RPCA produced three modes of drought variability that explain 74 percent of the variance in the drought frequency data. The first two modes of drought frequency are related to important indices of Northern Hemisphere climate variability; the Pacific Decadal Oscillation and the Atlantic Multidecadal Oscillation. The remaining mode of drought frequency is negatively correlated with mean annual Northern Hemisphere temperature and appears to reflect long-term trends in drought frequency in areas associated with this mode.

## 1. Introduction

Two important modes of Northern Hemisphere decadal climatic variability, the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO), are related to precipitation (and drought) variability in the conterminous United States (US) (Nigam et al, 1999; Enfield et al., 2001; Gray et al., 2003). The PDO is an index of sea-surface temperature (SST) variability in the North Pacific Ocean (Mantua and Hare, 2002) and the AMO is an index of SST variability in the North Atlantic Ocean (Enfield et al., 2001). Previous studies examined correlations between these climate indices and precipitation (or drought) in the conterminous US; however, the associations of the PDO and AMO with the principal modes of US drought frequency variance have not been established. The investigation of these associations will lead to increased understanding of PDO/AMO effects on the climate of North America, specifically through the influence of these modes on the probability of drought. In this study, drought frequency in the conterminous US is decomposed into its primary modes of variability without apriori consideration of climate forcing factors. These modes are then related both spatially and temporally to external climate forcing factors to identify the most important climate associations drought in the conterminous US.

## 2. Methods

Drought frequency for 20-year moving periods was calculated for each of the 344 climate divisions in the conterminous US for the period 1900-1999. This period of record was chosen for analysis because it is common to all of the data sets used in this study (i.e. climate division precipitation, annual PDO, and annual AMO). Drought conditions were considered to exist in a climate division if annual precipitation was in the lowest quartile of the 100-year record. For 20-year moving windows, the number of years with drought conditions was computed for each climate division and assigned to the center of the window period. The time series of 20-year moving drought frequencies (hereafter referred to as drought frequency) then were subjected to a rotated principal components analysis (RPCA) with varimax rotation to identify the primary modes of variability in the drought frequency data. The scores and loadings of the leading rotated principal components were subsequently examined and compared with 20-year moving averages of the AMO and PDO to better understand how these climate indices are related to the temporal and spatial variability of drought in the conterminous US.

The climate division precipitation data were obtained from the National Climatic Data Center in Asheville, North Carolina via the internet at (http://www1ncdc. noaa.gov/pub/data/cirs/). The PDO data also were obtained via the internet from the University of Washington at (ftp://ftp.atmos.washington.edu/mantua/pnw_impacts/INDICES/PDO.latest), and the AMO data were obtained by personal communication with David Enfield (NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida). Mean annual Northern Hemisphere (NH) temperature data also were used for part of the study and these data were obtained from the Climate Research Unit, East Anglia, United Kingdom at (http://www.cru.uea.ac.uk/cru/data/temperature/).

## 3. Results and discussion

The RPCA of drought frequencies for the 344 climate divisions in the conterminous US produced three leading components (PC1, PC2, PC3) that explain 74 percent (%) of the total variance in the drought frequency data; PC1 explains 29% of the total variance in drought frequency, PC2 explains 28%, and PC3 17%. The score time series (Figure 1) for these components illustrate the temporal variability of drought frequency, and the loadings (Figures 2a – 2c) illustrate the spatial pattern of drought frequency variability represented by each component.

### 3.1 Component 1

The scores for PC1 (Figure 1a) are positive for 20-year periods centered from around 1920 to the mid- to late 1940s, are negative from the late 1940s until the late 1970s, and are slightly positive after the 1970s. This decadal variability in drought frequency is similar to variability in the PDO (Figure 1a). The correlation between PC1 scores and 20-year moving mean annual PDO is 0.82. Despite the inherent autocorrelation induced by the 20-year moving window used in the analysis, the large magnitude of the correlation suggests that PC1 represents the effects of PDO on drought frequency in the conterminous US.

To further compare PC1 with PDO, the loadings of drought frequency for each climate division on PC1 (Figure 2a) were compared with correlations between 20-year moving average annual PDO and drought frequency for each climate division (Figure 2d). Comparison of these figures indicates that the patterns of the PC1 loadings and the PDO correlations are similar. Both indicate negative values for the southwestern US that extend into the Rocky Mountain region and the south central US (Figures 2a and 2d). Negative values also are found in the northeastern US. Positive values are indicated in the northwestern US, the north-central plains, and most of the southeastern US. The correlation between these patterns is 0.92. The PDO has been shown to modulate winter precipitation in the US (Mantua et al. 1997; McCabe and Dettinger, 1999; Gray et al., 2003). In addition, Nigam et al. (1999) examined correlations between PDO and summer (June through August) drought and summer streamflow in the conterminous US. The correlation patterns presented by Nigam et al. (1999) are similar to those illustrated in figures 2a and 2d. They conclude that the PDO is a potentially useful predictor of warm season drought variations in the US.

The strong correlation of the spatial patterns represented by the PC1 loadings and the PDO correlations (Figures 2a and 2d), when combined with the magnitude of the time series correlation, clearly supports the conclusion that the first mode of drought frequency identified in this study is related to the variability of the PDO. The annual response pattern is a combination of the summer influences shown in Nigram et al. (1999) and the winter influences shown in Mantua et al. (1997). While both seasons share a dipolar response in the northwest and southwest US, the response to the PDO in the Midwest is of different sign in the summer and winter, weakening the annual response in that region.

### 3.2 Component 2

The scores for PC2 increase from the early part of the record to the 20-year period centered around 1930. The score values remain relatively constant until after 1960, when they decline until the end of the period of record (Figure 1b). This time series corresponds to the temporal variability of the AMO (Figure 1b). The correlation between PC2 scores and 20-year moving average annual AMO is 0.91.

Loadings for PC2 (Figure 2b) and correlations between 20-year moving average annual AMO and drought frequency (Figure 2e) are highly similar (the correlation between these patterns is 0.95). Maps of the PC2 loadings and the AMO correlations indicate positive values for most of the central two-thirds of the conterminous US and suggest an almost nationwide covariance of drought frequency (Figures 2b and 2e). Gray et al. (2003) state that during positive AMO conditions, the central US receives below-average precipitation, particularly during summer. The large positive correlations between smoothed AMO and drought frequency for the central US (Figure 2e) support this statement.

This mode explains 28% of the drought frequency variance, slightly less than PC1, but covers a larger geographical area with uniformly strong loadings (the PC1 dominant divisions tend to be smaller in area). Enfield et al. 2001 found that correlations between smoothed AMO (10-year running mean) and similarly smoothed climate division precipitation data produced a continental-scale pattern of negative correlations. The pattern of Enfield et al. (2001) is the inverse of PC2, because the correlation is made with precipitation, the inverse of drought frequency. The findings of the two studies are consistent.

### 3.3 Component 3

Scores for PC3 indicate a trend in drought frequency (Figure 1c). The score time series does not appear to be related to known atmosphere-ocean modes of variability; instead, it matches well with mean annual NH temperature. In Figure 1c, the NH temperatures were multiplied by –1 for direct comparison with the scores for PC3.

Instrumental observations of global and NH temperatures indicate an increasing trend over the period of record used in this study (Karl et al., 1996), and inverse 20-year moving mean annual NH temperatures are highly correlated with PC3 scores (correlation coefficient = 0.91).

The strong relation between PC3 scores and the time series of NH temperatures (Figure 1c) also is supported by the similarity in the patterns of loadings for PC3 (Figure 2c) and the correlations between 20-year moving average annual NH temperature and drought frequency (Figure 2e). The NH temperature correlations illustrated in figure 2e were multiplied by –1 for easy comparison with PC3 loadings. The correlation between these maps is 0.93.

In addition, the loadings pattern for PC3 and the pattern of inverse NH temperature correlations are similar to the trends in drought frequency and the inverse of the pattern of trends in US annual precipitation (Karl et al., 1996). Trends in drought frequeney were computed for each climate division using simple linear regression. The correlation between PC3 loadings and trends in drought frequency is –0.91, and the correlation between inverse NH temperature correlations and trends in drought frequency is –0.87. These results suggest that PC3 reflects regional trends in drought frequencies that are potentially related to increases in NH temperature. Climate modeling studies indicate a substantial intensification of the global hydrologic cycle is likely in a warming world, although the regional patterns of response are likely to be complex (Houghton et al. 2001).

## 4. Conclusions

Three rotated principal components explain 74% of the variance in 20-year moving frequencies of drought in the conterminous US. The first component is highly correlated with the PDO and the second component is correlated with the AMO. These first two components explain nearly equal proportions of variance in the entire data set and combined explain 57% of the total variance. These results support previous research that has indicated a relation between these climate indices and drought variability in the US. The third component indicates a trend in drought frequency and is highly correlated with NH temperature. The complexity of some portions of the spatial associations may be caused by grouping the underlying data by annual periods. Work is presently underway to examine the seasonality of these relationships.

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**Figure 1.** Scores from the first three components (PC1, PC2, and PC3) of a rotated principal components analysis of 20-year moving drought frequency in the conterminous United States, and standardized departures of 20-year moving averages of the annual Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), and Northern Hemisphere temperature (NH Temp). The NH Temp values are multiplied by –1 for easy comparison with PC3 scores. All values are plotted at the centers of the window periods.

**Figure 2.** (A through C) loadings for the first three components of a rotated principal components analysis of 20-year moving drought frequency in the conterminous United States, (D) correlations between 20-year moving drought frequencies and 20-year moving annual Pacific Decadal Oscillation (PDO), (E) correlations between 20-year drought frequency and 20-year moving Atlantic Multidecadal Oscillation (AMO), and (F) correlations between 20-year drought frequency and 20-year moving average annual Northern Hemisphere temperature (NH Temp). The correlations in F were multiplied by –1 for easy comparison with other figures. Positive values are shaded red and negative values are shaded blue. Darker shades indicate values greater than 0.4 or less than –0.4.

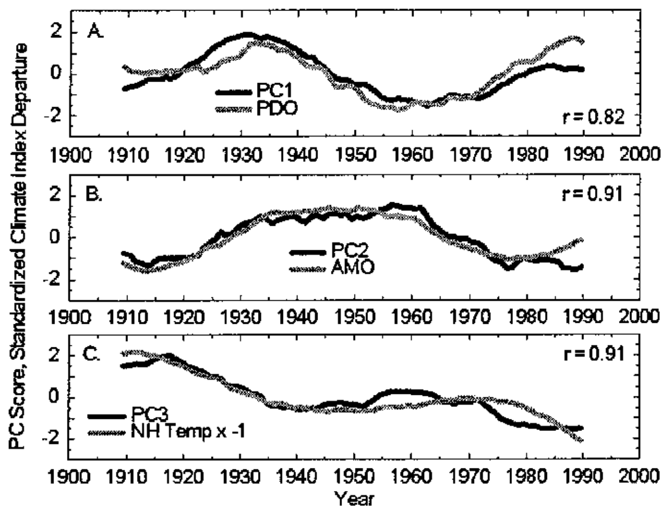


Figure 1. Scores from the first three components (PC1, PC2, and PC3) of a rotated principal components analysis of 20-year moving drought frequency in the conterminous United States, and standardized departures of 20-year moving averages of the: (A) annual Pacific Decadal Oscillation (PDO); (B) Atlantic Multidecadal Oscillation (AMO); and (C) Northern Hemisphere temperature (NH Temp). The NH Temp values are multiplied by –1 for easy comparison with PC3 scores. All values are plotted at the centers of the window periods.

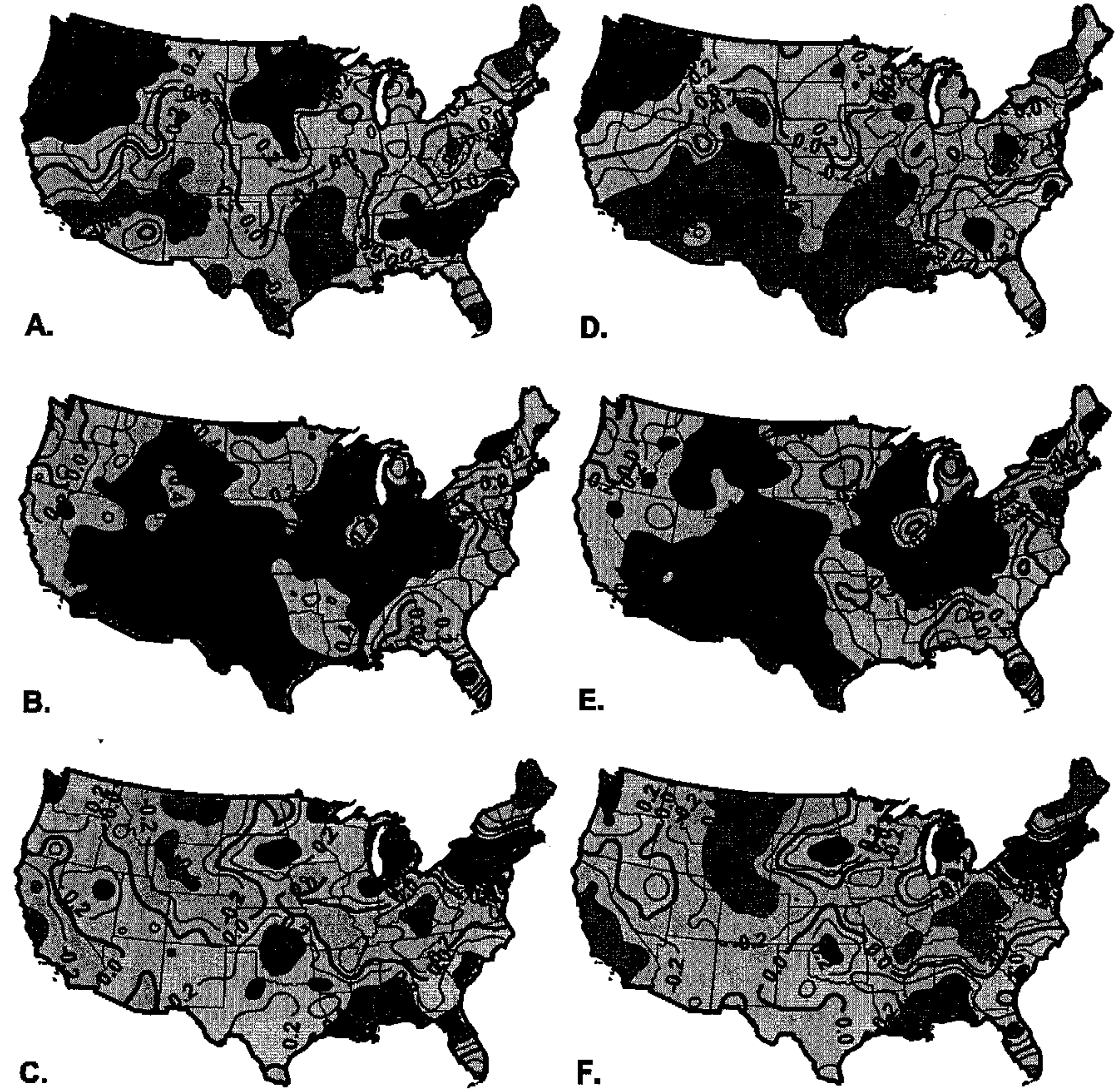


Figure 2. (A through C) loadings for the first three components of a rotated principal components analysis of 20-year moving drought frequency in the conterminous United States, (D) correlations between 20-year moving drought frequencies and 20-year moving annual Pacific Decadal Oscillation (PDO), (E) correlations between 20-year drought frequency and 20-year moving Atlantic Multidecadal Oscillation (AMO), and (F) correlations between 20-year drought frequency and 20-year moving average annual Northern Hemisphere temperature (NH Temp). The correlations in F were multiplied by −1 for easy comparison with other figures. Positive values are shaded red and negative values are shaded blue. Darker shades indicate values that are greater than 0.4 or less than −0.4.